Control system instrumentation

DINAMICA E CONTROLLO DEI PROCESSI CHIMICI
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Co. MolBNL
MOLECULAR BIOLOGY AND
NANOTECHNOLOGY LABORATORY
UNIVERSITY OF TRIESTE

ANDREA MIO, PhD
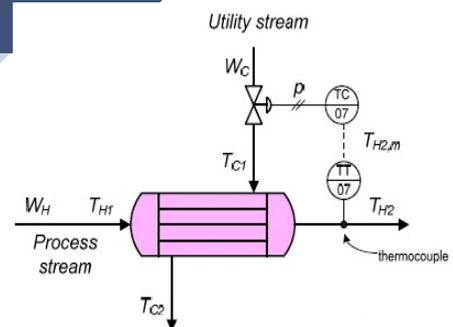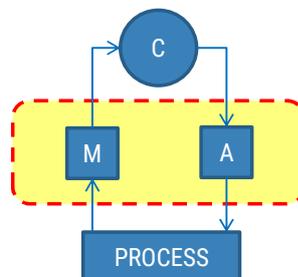MolBNL @ DIA-UniTS; www.molbnl.it
amio@units.it - 0405583440

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CONTROLLER/PROCESS INTERFACE

- **Measurement** of the required variable
- **Transmission** of the signal
- **Manipulation** of the manipulated variable

Controller/Process interface

C= Controller
M= Measurement sensor
A= Actuator (final control element)

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SENSOR, TRANSMITTERS AND TRANSDUCERS

- A **sensor** produces a physical response (e.g., electrical or mechanical) related to the value of the variable that is being measured
  - ▻ Example: a thermocouple generates a signal in [mV], which increases as the process stream T increases
- A **transmitter** then transmits the measurement signal to the controller
  - ▻ The signal is converted into the controller standard input form (current or voltage)

Process variable → | SENSOR-TRANSMITTER | → Signal transmitted (to the controller)
$$4 - 20\ mA$$
$$1 - 5\ V\ dc$$

- A **transducer** converts an instrumentation signal from one form to another
  - ▻ Example: to convert the controller output (current) to a command signal for a valve (pneumatic), a current-to-pressure (I/P) transducer is used

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STATIC CHARACTERISTICS OF SENSORS

- **Range**
  - ▻ Maximum and minimum sensor readings
    - ❖ Example in the figure: range is 50-150 °C
- **Zero**
  - ▻ Lowest reading available from the sensor (usually resulting in a 4 mA transmitter output signal)
    - ❖ Example: in the figure: the instrument zero is 50 °C
- **Span**
  - ▻ Difference between the high and low values of the range
    - ❖ Example in the figure: the span is (150-50)=100 °C
- The zero and the span are typically set by the user
- It is always advisable to have a **linear** relation between the measured variable and the signal transmitted ($\rightarrow$ constant gain Km of the sensor)

$$K_m = \frac{output\ range}{transmitter\ span} = \frac{(20 - 4)mA}{(150 - 50)°C} = 0.16\ mA/°C$$

Typically, the sensor gain is **positive**

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DYNAMIC CHARACTERISTICS OF SENSORS

- **Sensor dynamics**
  - ▹ Refers to how rapidly a sensor output signal $y_{meas}(t)$ tracks a true change of the measured variable $y_{true}(t)$
- In most cases, the sensor response is similar to that of a **FO system**

$$G_m(s) = \frac{Y_{meas}(s)}{Y_{true}(s)} = \frac{K_m}{\tau_m s + 1}$$

True Value $Y_{true}(s)$ → **SENSOR-TRANSMITTER** → Measured signal $Y_{meas}(s)$

- The sensor time constant should always be **much smaller** than the dominant time constant of the process ($\tau_m \ll \tau_p$)
  - ▹ **At least 10 times smaller**; better if even smaller
  - ▹ Hence, a sensor is selected appropriately if it shows **negligible dynamics** (i.e., fast dynamics) with respect to the measured variable dynamics
- In some cases, the sensor dynamics **cannot be neglected**
  - ▹ Simple thermocouple vs thermocouple with thermowell → FO dynamics
  - ▹ Bad dynamic response due to bad sensor placement can generate a dead time
    - ❖ A pH-meter installed in the outlet pipe instead than inside the neutralization tank generates a distance-velocity lag in the sensor response
    - ❖ A process gaschromatograph requires time to perform the measurement

Time-delay dynamics

$$G_m(s) = K_m e^{-\theta_m s}$$

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TERMINOLOGY ON SENSORS-TRANSMITTERS /cont'd

- **Accuracy**
  - ▹ Difference (measurement error ε) between the value of the measured variable indicated by the sensor and its true value
    - ❖ Since the true value is never known, accuracy is usually estimated by the difference between the sensor value and an accepted standard
  - ▹ The error ε is expressed as **% of full scale** (%FS; % span) or as **% of the measured value**

$$\varepsilon_{FS} = \frac{|y_{meas} - y_{true}|}{span} \times 100 \qquad \varepsilon_{meas} = \frac{|y_{meas} - y_{true}|}{y_{meas}} \times 100$$

  - ▹ Lack of accuracy is usually due to **systematic error** (bias)
    - ❖ In most cases, related to improper calibration or inappropriate installation of the sensor
- **Precision**
  - ▹ Refers to the **variability of the measurement** carried out with a given instrument under assigned (fixed) conditions
  - ▹ It is usually expressed in terms of standard deviation or range of the readings
  - ▹ Example:
    - ❖ The composition of four samples of a given liquid solution is measured with a given instrument
    - ❖ Four different concentration readings are obtained, e.g. 21.3%, 22.7%, 20.6%, 21.5%
    - ❖ The instrument precision is (22.7-20.6)=2.1% (range) or 0.873% (std.dev. of the readings)

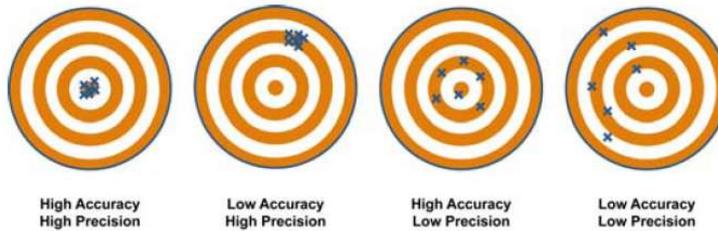Adapted from Barolo M

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TERMINOLOGY ON SENSORS-TRANSMITTERS /cont'd

- **Repeatability**
  - ▷ Same as precision
  - ▷ Expresses the variation in measurements taken by a single instrument on the same item and under the same conditions
  - ▷ Lack of precision/repeatability derives from **random errors** due to known or unknown sources (noise)
    - ❖ Precision can be improved using the **average** of several readings

High Accuracy High Precision | Low Accuracy High Precision | High Accuracy Low Precision | Low Accuracy Low Precision

- For process control, **precision** is usually more important than accuracy

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TERMINOLOGY ON SENSORS-TRANSMITTERS /cont'd

- **Bias (systematic error)**
  - ▷ Difference (due to deterministic causes) between the average of several sensor readings and the true value
    - ❖ Example: if a thermocouple is installed in a tank, but it is in contact with the tank wall, the temperature measurement may be systematically smaller than the true value due to conduction losses
- **Rangeability (turn-down)**
  - ▷ Ratio between the upper limit and the (normalized-to-one) lower limit of the instrument range within which the instrument precision and accuracy values are valid
    - ❖ Example: a mass flow sensor with 20:1 rangeability, 100 kg/s full scale, and 1% accuracy, measures with that accuracy flowrates between 5 and 100 kg/s
    - ❖ Notice:
      - ▪ Some manufacturers define rangeability as the ratio between the (normalized-to-1) lower measurement limit and the upper limit (full scale), both set by the user

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TYPICAL CHARACTERISTICS OF SENSORS FOR PROCESS CONTROL

Sensor	Time constant (s)	Repeatability	Rangeability or range
Thermocouple with thermowell	6-20	±1 °C	-200 to 1300 °C
Resistance temperature detector with thermowell	6-20	±0.1 °C	-200 to 800 °C
Thermistor with thermowell	6-20	±0.1	
Magnetic flow meter	<1	±0.1 %	20:1
Vortex flow meter	<0.1	±0.2 %	15:1
Orifice flow meter	<0.2	±0.3 to ±1 %	3:1
Coriolis flow meter	<0.1	±0.1 to ± 0.5 %	10:1
Differential pressure level indicator	<1	±1 %	9:1
Pressure sensor	<0.2	±0.1 %	9:1
pH-meter	2-5	±0.1 pH units	4 to 8 pH units

Riggs and Kharim, 2006

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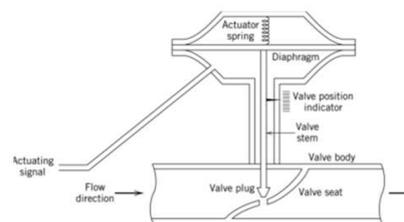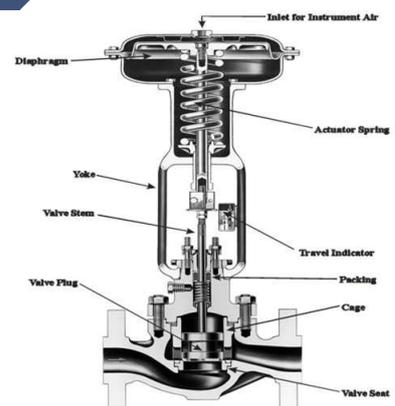## CONTROL VALVES

- They are the most frequent final control element
  - ⊳ Used to modulate the **material or energy flow** to/from a process
  - ⊳ Other final control elements: variable-speed pumps, electrical resistances, variable-speed conveyor belts, etc…

(Seborg *et al.*, 2011)

(Riggs & Karim, 2006)

- Elements of a stem valve:
  - ⊳ Body or «corpo»
  - ⊳ Seat or «sede» or «seggio»
  - ⊳ Plug or «otturatore»
  - ⊳ Stem or «stelo»
  - ⊳ Actuator or «attuatore»

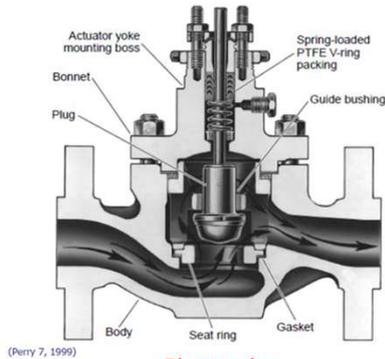Adapted from Barolo M

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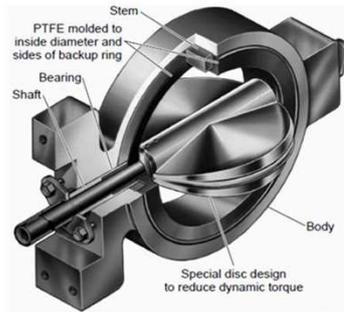© Andrea Mio, University of Trieste

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GLOBE VALVES (RISING STEM) AND ROTARY VALVES

- In globe valves, the plug travel is orthogonal to the flow
  - ▷ These valves should be installed so that the flow tends to open them
    - ❖ Hence, when the valve is closed, seals are not subjected to pressure

Piston valve
(linear stem motion)

(Perry 7, 1999)

Butterfly valve
(rotary stem motion)
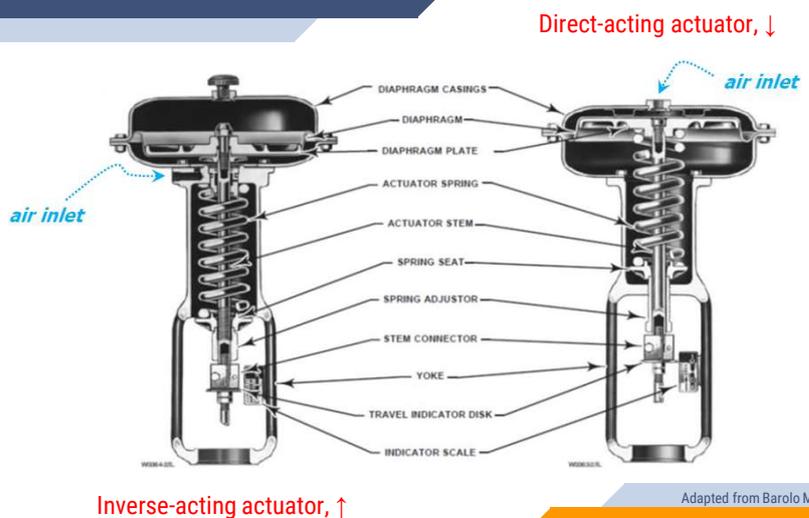
(Perry 7, 1999)

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ACTUATOR

Direct-acting actuator, ↓

air inlet

- Converts the inlet signal (pneumatic or electric) into a stem movement, which is required to open or close the valve
  - ▷ The most popular actuator is the (pneumatic) **membrane actuator**
  - ▷ The fact that the valve results an air-to-open or an air-to-close one depends on the combination of the actuator action and the valve body action

air inlet

DIAPHRAGM CASINGS
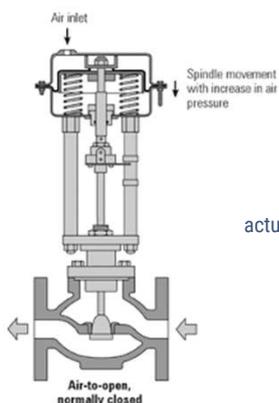DIAPHRAGM
DIAPHRAGM PLATE
ACTUATOR SPRING
ACTUATOR STEM
SPRING SEAT
SPRING ADJUSTOR
STEM CONNECTOR
YOKE
TRAVEL INDICATOR DISK
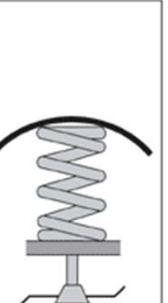INDICATOR SCALE

Inverse-acting actuator, ↑

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ACTUATOR ACTION AND VALVE ACTION

Air inlet

Spindle movement with increase in air pressure

Effect of different combinations of actuator/valve configurations

Actuator action	Direct	Reverse	Reverse	Direct
Valve body action	Direct	Reverse	Direct	Reverse
Valve action	Air-to-close	Air-to-close	Air-to-open	Air-to-open

Air-to-open, normally closed

Direct-acting actuator on reverse-acting valve body

http://tijarohonline.blogspot.com/2010/12/actuator.html

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VALVE DEADBAND

- It is a measure of how precisely a control valve can modulate the flow
  - It is the maximum relative change in the signal to a control valve that does **not** produce a measureable change in the flow rate
    - ❖ Deadband is caused by the friction between the valve stem and the valve packing, as well as by other forces acting on the valve stem
    - ❖ Example: a valve has a deadband of 10% → only a change in the command signal to the control valve **greater** than 10% will result in a measurable change in the flow through the valve

- Typically, industrial control valves **without a positioner** have a deadband of **10 to 25%**
  - The larger and older the valve, the larger its deadband

- A properly functioning valve (with a valve **positioner**) typically has a deadband **≤0.5%**
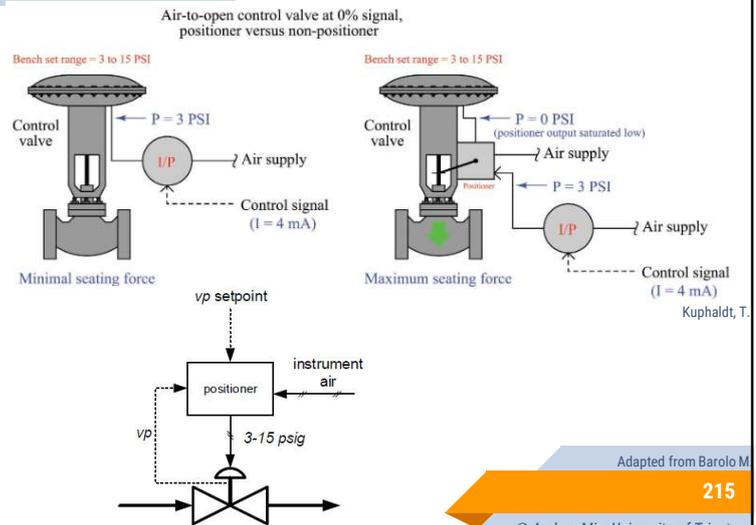
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ANCILLARY EQUIPMENT: VALVE POSITIONER

- Often, the valve stem position cannot be mantained precisely at the desired value
  - ▻ Stem friction due to valve packing or «premistoppa»
  - ▻ Friction due to fluid viscous forces
  - ▻ Delay (for large actuators)
  - ▻ Pressure variations in the line
  - ▻ Deadband

- In these cases the valve may be equipped with a positioner or «posizionatore»
  - ▻ In fact, it is a high-gain proportional controller
    - ❖ CV: stem position
    - ❖ MV: instrument air fed to actuator
    - ❖ SP: may be the pneumatic signal from the I/P transducer or a digital signal from the distributed control system (DCS)

Air-to-open control valve at 0% signal, positioner versus non-positioner

Bench set range = 3 to 15 PSI

Control valve — P = 3 PSI
I/P — Air supply
Control signal (I = 4 mA)
Minimal seating force

Bench set range = 3 to 15 PSI

Control valve — P = 0 PSI (positioner output saturated low)
Positioner — P = 3 PSI
Air supply
I/P — Air supply
Control signal (I = 4 mA)
Maximum seating force

Kuphaldt, T.

vp setpoint
positioner ← instrument air
vp
3-15 psig

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ANCILLARY EQUIPMENT: VALVE POSITIONER /cont'd

- The positioner works at a frequency that is **greater** than that of the «main» controller
  - ▻ The main controller might be a TC manipulating the flow set-point of a given stream

- The typical control interval for a DCS is ~1.0 s
  - ▻ For **flow** control loops that are controlled by a DCS, a **valve positioner is a necessity**, because this control interval is not fast enough for most flow control loops
  - ▻ A **digital valve positioner** works at a higher frequency

- A positioner can significantly reduce the valve deadband
  - ▻ E.g., from ±5% (without positioner) to **0.5%** with positioner

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RANGEABILITY OF A CONTROL VALVE

- **Rangeability** (turndown ratio)
  - ▻ It is the ratio between the maximum signal to a valve and the minimum signal to that valve that still allow the flow rate to be modulated precisely
  - ▻ Typically: $95\%/5\% = \mathbf{19}$ or $90\%/10\% = \mathbf{9}$

- Alternatively it is expressed as: $\dfrac{flow\ at\ 95\%\ valve\ position}{flow\ at\ 5\%\ valve\ position}$

- Usually, for valve openings smaller than 5-10%, the plug hits the seat while trying to keep the valve less than 5-10% open
  - ▻ Hence, the valve wears out quickly
  - ▻ This occurrence is more frequent for overdesigned valves

- If valves open more than 90-95%, precise flow rate modulation is difficult (if not impossible)
  - ▻ This occurrence is more frequent for underdesigned valve

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FLOW COEFFICIENT OF A VALVE

- We are interested to understand how to determine the **appropriate size of a control valve** for a given service
  - ▻ We only consider case of <u>liquid streams not subject to phase change</u>
- In a pipe, a valve behaves like a restriction
  - ▻ For turbulent flow, the pressure drop ΔP_V across the valve is $\boxed{\Delta P_V = \mathrm{k}\rho \dfrac{v^2}{2}}$

$k \rightarrow$ depends on the form of the restriction
$\rho \rightarrow$ average fluid density (incompressible fluid)
$v \rightarrow$ fluid velocity across the restriction (whose cross-sectional area is A)
$q \rightarrow$ volumetric flow rate= $v \cdot A$

$$v = \sqrt{\frac{2\Delta P_V}{\mathrm{k}\rho}} \quad \rightarrow \quad q = A\sqrt{\frac{2\Delta P_V}{\mathrm{k}\rho}} = A\sqrt{\frac{\rho_{ref}}{\rho_{ref}}}\frac{A_{max}}{A_{max}}\sqrt{\frac{2\Delta P_V}{\mathrm{k}\rho}} = \sqrt{\frac{2A_{max}^2}{\mathrm{k}\rho_{ref}}}\frac{A}{A_{max}}\sqrt{\frac{\Delta P_V}{(\rho/\rho_{ref})}}$$

- If the reference fluid *ref* is **water** (at room temperature) and **English units** are used, the volumetric flow rate q across the valve can be expressed as:

$$\boxed{q = C_v f(\ell)\sqrt{\frac{\Delta P_V}{\rho_{rel}}}}$$

$C_v > 0 \rightarrow$ **Flow coefficient** (capacity factor) [gpm/psi$^{0.5}$] or «coefficiente di flusso»

$0 \leq \ell \leq 1 \rightarrow$ stem lift or «sollevamento dello stelo»

$0 \leq f(\ell) \leq 1 \rightarrow$ valve characteristic or «caratteristica della valvola»

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FLOW COEFFICIENT OF A VALVE   /cont'd

(1) $\quad q = C_v f(\ell) \sqrt{\dfrac{\Delta P_V}{\rho_{rel}}}$

- C_v is the flow, in US gallon/min [gpm], of water that flows through a valve when the valve is completely open and the pressure drop across it is 1 psi
- A similar definition exist in European units [cum/h], [bar]; the flow coefficient is indicated by K_v; the following relation exists: $K_v = 0.865 \cdot C_v$

- Equation (1) is sometimes written as: $\quad q = C_v(\ell)\sqrt{\dfrac{\Delta P_V}{\rho_{re}}}, \quad C_v(\ell) = C_{v,max}f(\ell)$

- The valve size can be selected from a catalogue if the C_v value required for that valve is known
  - Given the flow rate q that needs to be delivered through the valve, the required («rated») C_v value can be calculated from (1)
  - For this C_v value, the manufacturer's catalogue provides the required valve diameter
- Remarks
  - The flow rate q increases as C_v increases
  - C_v increases with the valve cross sectional area A_{max}
  - Other conditions being equal, the greater the C_v required for a given service, the greater the valve size to choose (and greater the cost)

$$C_v = \sqrt{\frac{2A_{max}^2}{k\rho_{ref}}}$$

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INHERENT FLOW CHARACTERISTIC OF A CONTROL VALVE

$$q = C_v f(\ell)\sqrt{\frac{\Delta P_V}{\rho_{re}}} \rightarrow C_v = \frac{q}{f(\ell)\sqrt{\dfrac{\Delta P_V}{\rho_{rel}}}}$$

$$f(\ell) = \frac{A}{A_{max}}$$

$$q = C_v(\ell)\sqrt{\frac{\Delta P_V}{\rho_{rel}}}, \qquad C_v(\ell) = C_{v,max}f(\ell)$$

- To size a valve (i.e., to determine its C_v), it is necessary to know:
  - Its flow characteristic $f(\ell)$ that indicates how the fraction of maximum flow across the valve varies with ℓ
  - The pressure drop ΔP_V across the valve
- Typical valve characteristics:
  - Linear valve: $f(\ell) = \ell$
  - Quick opening valve or «apertura rapida»: $f(\ell) = \ell^{1/\alpha}$
    - α is a constant parameter (o.o.m. $\cong$ 2-4; e.g., $f(\ell) = \sqrt{\ell}$)
  - Equal percentage valve or «equipercentuale» : $f(\ell) = R^{\ell-1}$
    - R is a constant parameter (Rangeability parameter; o.o.m. $\cong$ 20-50)

- The valve characteristics are inherent flow characteristics of a valve and are provided by the manufacturer
  - For a given valve, the inherent flow characteristics $f(\ell)$ profile is equal to the profile $\dfrac{q}{q_{max}}$ only if the pressure drop ΔP_V across the valve is constant

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THE DECISIONS TO BE TAKEN

- If we have to select a control valve, there are **two** important decisions to take (in addition to selecting materials and packing)
  - ▷ Which **size** should the valve have? → selecting C_v
    - ▷ Notice: the maximum flow across a valve (wide-open valve) does not depend on the valve characteristic
  - ▷ Which **flow characteristic** should the valve have? → linear, equal percentage, quick opening

- We need to understand how the ΔP_V **across the valve affects** both decisions

  - ▷ Does $\boldsymbol{\Delta P_V}$ **change** during normal operation?

  - ▷ If ΔP_V changes, does the flow **characteristic also change**?

  $$C_v = \frac{q}{f(\ell)\sqrt{\dfrac{\Delta P_V}{\rho_{rel}}}}$$

  - ▷ Which value should we **assign to $\boldsymbol{\Delta P_V}$** when we size the valve?

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